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Observation of Large-Scale Traveling Ionospheric Disturbances by Spaced-Path, H-F, Instantaneous-Frequency Measurements

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RADIOSCIENCE LABORATORY

STANFORD ELECTRONICS LABORATORIES

STANFORD UNIVERSITY · STANFORD, CALIFORNIA

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ABSTRACT

The instantaneous frequency of WWV, 20 Mc (Washington, D. C.), and that of a highly stable signal at 17.8 Mc radiated from Mayaguez, Puerto Rico, were simultaneously and continuously recorded between October 1960 and September 1961 at Palo Alto, California, and at Seattle, Washington. Traveling ionospheric disturbances (TID's) have been identified on these recordings by noting the occurrence of similar frequency fluctuations appearing with appropriate time delays, and in the appropriate order, on each of the four available paths. The geometry of these paths is such that disturbances traveling from north to south, or vice-versa, are most easily detected.

It is found that the disturbances give rise to either quasi-sinusoidal, or V-shaped fluctuations in the recordings of frequency vs. time. If a given disturbance is assumed to travel along a great circle at a constant speed, this speed can be estimated from the time interval between interception of the northernmost transmission path and the southernmost one (a minimum distance of about 1200 km). From the duration of the resulting fluctuation on a given path and the estimated speed of the disturbance, its effective spatial length can be inferred.

Because of the wide separation of the long-distance transmission paths, the experimental setup is sensitive only to large-scale TID's moving at high speed. Such disturbances would probably not be detectable on recordings made with the comparatively close receiver spacing used by many researchers in the past. From 1600 hours of data (usually from 1600 UT to 0200 UT) between October 1960 and April 1961, nine TID's have been positively recognized on the frequency recordings. It was possible to deduce speeds and lengths (on the above assumptions) in six instances. Velocities range from 1450 km/hr, and spatial lengths from 1300 km to greater than 2000 km. The direction of travel cannot be determined accurately, but, in each case, the general direction is from north to south. The results suggest that certain of the TID's change their velocity and/or direction of travel during the passage through the four transmission paths. In four cases, sudden frequency changes, correlated with sudden changes in the earth's magnetic field recorded at Stanford University, preceded the occurrence of large-scale TID's. It is suggested that these traveling disturbances may have been launched by the same event giving rise to the sudden change in the earth's magnetic field.

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I. INTRODUCTION

Horizontal traveling disturbances in the ionosphere have been studied extensively by Munro [Refs. 1-4] and many other workers [Refs. 5-13], employing closely spaced networks. Traveling ionospheric disturbances (TID's) were observed by a variety of techniques, including group-path-vs.-time records [Refs. 1-9], and signal-intensity-vs.-time records [Refs. 10-13] of received signals transmitted at fixed frequencies from two or more stations, separated by a few tens of kilometers to not more than 500 km. Traveling ionospheric disturbances at heights above the F_2 maximum (400 km) have been studied by the radio-star-scintillation technique [Refs 14-16]

Traveling ionospheric disturbances can also be detected by studying the variation with azimuth of the minimum range of ground backscatter seen on a rotating-antenna fixed-frequency backscatter sounder. [Refs. 17,18]. This technique, developed by Valverde [Ref. 17], at Stanford University, has the advantage that the directions and the velocities of disturbances can be determined at one station. This technique is particularly useful for detecting large, wide-spread disturbances. But it requires continuous, pulsed, sounding transmissions.

In this report, TID's in the F_2 layer in a non-auroral region are investigated by observing their effect on the instantaneous received frequency of four stable h-f transmissions. The four transmissions are considered to be stable since the frequency fluctuations imposed by the ionosphere are much larger than the inherent frequency fluctuations of the transmitting and receiving systems.

The four geographically separated transmission paths extend over distances from 3750 to 6000 km in the east-to-west direction. The northermost and the southermost paths are separated by more than 1200 km. Because of the comparatively wide spacing of this network, only large-scale and high-speed TID's, whose morphology does not change appreciably in the time interval between path crossings, are detected. Traveling ionospheric disturbances distinguishable by this technique prove to be very rare, and their indicated velocities have been very high. Observed velocities ranged from 1450 to 2700 km/hr as compared with the velocities observed by other researchers, as listed below.

Researcher	Velocity Range (km/hr)	Remarks
Munro [Ref. 4]	420 - 500	monthly average
Price [Ref. 5]	120 - 1200	maximum no. at 600 km/hr
Toman [Ref. 6]	250 - 600	maximum no. at 350 km/hr
Beynon [Ref. 7]	420	
Ramachandra Rao [Ref. 12]	540 1200	
Maxwell and Little [Ref. 14]	430	average
Hewish [Ref. 15]	360 - 1100	at about 400-km height
Maxwell and Dagg [Ref. 16]	180 - 1100 720 - 1800	in non-auroral regions in auroral region about 400 km
Valverde [Ref 17]	700 - 2000	
Tveten [Ref. 18]	200 - 1100 up to 4500	for small-scale disturbances for large-scale disturbances

With stable transmissions already available from standard-frequency broadcasting stations in the U. S. A., Canada, and other parts of the world, a network covering a large portion of the world could be established comparatively economically by establishing suitable receivers at the appropriate locations.

The equipments of this experiment are briefly described in Section II, and the results are presented in Section III, followed by discussion and conclusions in Sections IV and V. A possible association between the occurrence of the large-scale traveling disturbances and the sudden commencements of geomagnetic storms is discussed in Section IV but, unfortunately, the limited information obtained in this experiment allows only a preliminary conclusion to be made.

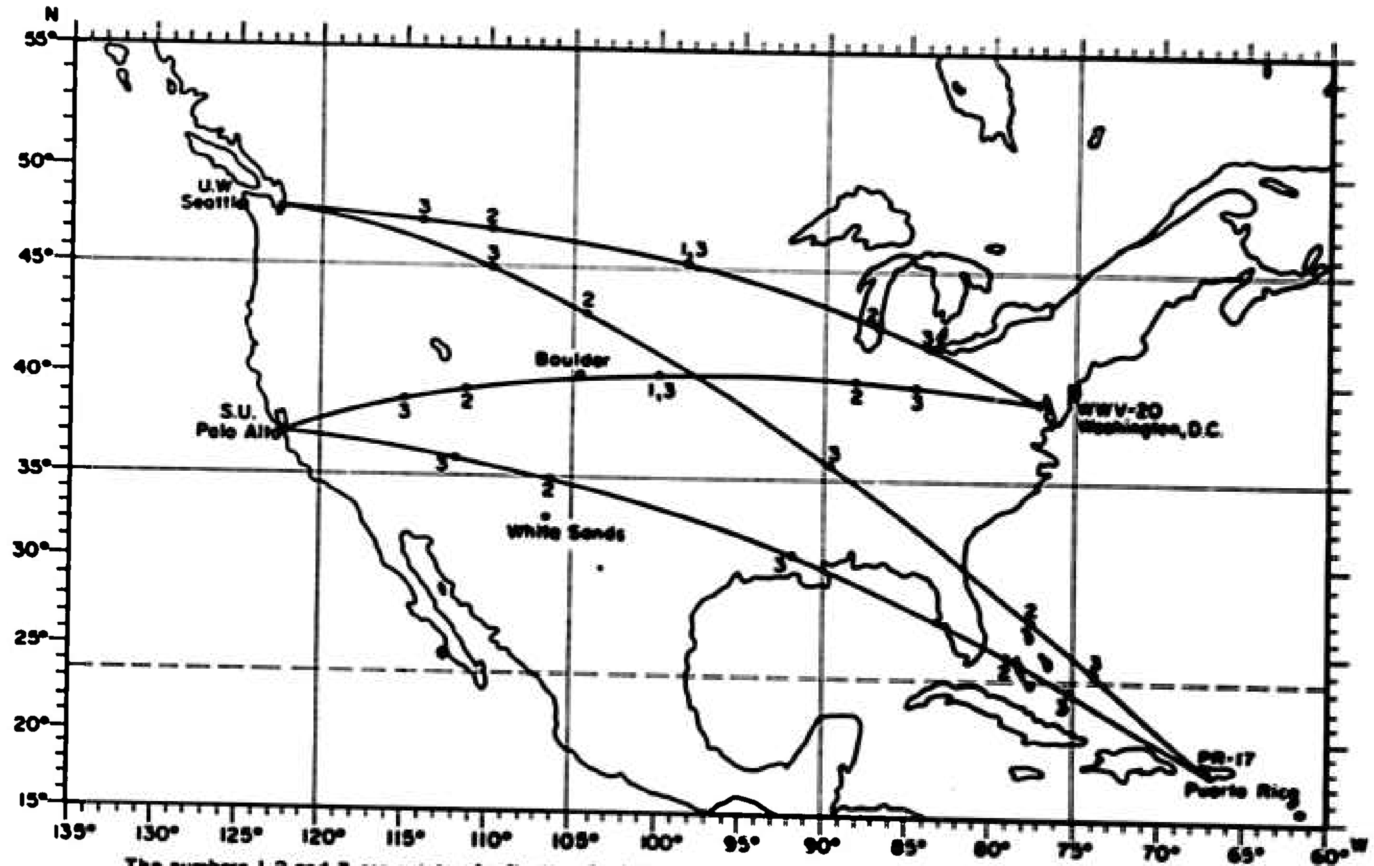
II. EXPERIMENTAL ARRANGEMENTS

From October 1960 to September 1961, stable-frequency transmissions of 17.8825 Mc from Puerto Rico (referred to as PR-17) and 20 Mc from WWV, Washington, D. C. (referred to as WWV-20) have been simultaneously and continuously recorded at Stanford University (referred to as SU), near Palo Alto, California, and at the University of Washington (referred to as UW), Seattle, Washington. The four transmission paths are shown in Fig. 1. The numbers 1, 2, and 3 are points of reflection in the ionosphere for the 1-hop, 2-hop, and 3-hop modes of propagation. The WWV-20-to-UW and WWV-20-to-SU paths, approximately 3750 km and 3950 km in ground distance, respectively, will support 1-hop, 2-hop, and 3-hop modes of propagation, whereas PR-17-to-UW and PR-17-to-SU paths, approximately 6000 km and 5750 km in ground distance, will support primarily 2-hop and 3-hop modes of propagation.

The PR-17 signal is transmitted on a three-element beam Yagi antenna with about 600-w average power. A Rhode and Schwarz XUD frequency synthesizer is used to generate the frequency at 17.8825 Mc with stability better than a few parts in 10^9 per day. The WWV-20 signal is transmitted on a nondirectional antenna with about 10-kw average power. Its stability is better than one part in 10^{10} per day. At the radio frequencies used, frequency fluctuations cased by the ionosphere are large compared with the inherent frequency fluctuations of the sources.

Parts of the receiving system have been previously reported by Fenwick and Villard [Ref. 19]. However, in the present setup, a Rhode and Schwarz XUD frequency synthesizer is used, along with the Rhode and Schwarz XSA frequency standard to beat with the incoming signals. The frequency beat note(usually in the 0- to 10-cps range), is fed into a frequency meter that produces a rectangular pulse at each input-signal zero-crossing. The frequency meter output is then recorded on a Sanborn paper-tape recorder. A coded time-marking signal is introduced into the system at the beginning of each hour to facilitate the identification of the time. This counter-type system responds to the instantaneous frequency of that mode of propagation which is strongest at any given instant. The over-all accuracy of the system is about 0.2 cps.

In addition to the counter-type recordings described above, the 0 - 10-cps signal itself is also direct-recorded on a modified Webcor magnetic-tape recorder whose speed is approximately 1/50 in./sec [Ref. 20]. The magnetic tape is played back at a much higher speed, usually at



The numbers 1,2 and 3 are points of reflection for 1-hop, 2-hop and 3-hop mode of propagation in the ionosphere.

	Great Circle Distance	
Seattle to Washington, D.C.	3750	Km
Palo Alto to Washington, D.C.	3950	"
Seattle to Puerto Rico	6000	"
Palo Alto to Puerto Rico	5750	"

FIG. 1. GREAT-CIRCLE PATHS OF WWV-20 AND PR-17 TO SU AND UW.

15 in./sec, into a Kay Electric Company Sonalyzer to obtain a frequency-amplitude-time record, which is known as a "Sonagram", with frequency along the vertical axis, time along the horizontal axis, and amplitude shown by the darkness of the pattern. The Sonalyzer accepts a frequency band extending from 85 to 8000 cps. In this instrument, the bandwidth of the tuned circuit, which scans through the frequency range, is 45 cps, and an individual Sonagram represents an input time interval of 2.4 sec. As a consequence of speeding up the magnetic tape approximately 800 times, the effective bandwidth of the selective circuit is about 1/16 cps, and the time is also effectively compressed by a similar amount. As a result, a single-frequency signal component must last for at least 15 to 20 sec in real time to register a readable pattern on the final record. The "Sonagram", in contrast with the counter-type record, permits study of the behavior of different propagating modes with different frequencies if more than one such mode is present at a given time. The accuracy of this system is also about 0.2 cps.

Any frequency fluctuation greater than 0.2 cps can be regarded as due to variations of or disturbances in the ionosphere. The simultaneous recordings of signals transmitted along four separate paths make it possible to distinguish widespread ionospheric disturbances, such as those due to solar flares, world-wide magnetic storms [Ref. 21], etc., from TID's. The following sections report the rarely observed evidences of large-scale TID's studied by means of this technique.

III. RESULTS

The four transmission paths shown in Fig. 1 have been in use between October 1960 and September 1961 except for periods of equipment failure or poor propagating conditions in the ionosphere. Under normal conditions in winter, WWV-20 and PR-17 usually come in in the morning around 1400 UT, and fade out in the evening around 0200 UT, with slight time variations for different paths. A study has been made of about 1600 hours of recordings obtained between October 1960 and April 1961 during which time at least three of the four paths were usable. Traveling ionospheric disturbances (TID's) have been identified on these recordings by noting the occurrence of similar frequency fluctuations appearing with appropriate time delays, and in the appropriate order, on each of the four available paths. Only nine TID's have been positively recognized by means of these particular multi-station, stable frequency transmissions during this period. These nine are described in chronological order and are numbered accordingly in Table I, and two (Nos. 1 and 5) are discussed in more detail in Sections III A and B respectively.

A. TRAVELING IONOSPHERIC DISTURBANCE OF 12 AND 13 DECEMBER 1960

Figure 2 presents counter-type records of the instantaneous frequency variation of signals propagated along the four transmission paths on 12 and 13 December 1960. These signals are WWV-20 received at UW, PR-17 also received at UW, WWV-20 received at SU, and PR-17 received at SU, all displayed on the same time scale. The WWV-20 signals have a cut-off period from approximately 45 to 49 min after each hour. Calibration marks introduced at the receiving stations at 15-min intervals appear on three of the four recordings, and hourly time marks are also placed on the recording of the PR-17-to-SU signal.

An ionospheric disturbance can be recognized on the WWV-20-to-UW signal by the V-shaped inflection in the frequency recordings from 2330 to 0015 UT. The relative frequency of WWV-20 at UW decreases at the rate of about 3-1/2 cps in a half hour to a minimum near 2354 UT. It then increases back to the normal propagating frequency at a higher rate. A similar V-shaped inflection can be recognized on the records of the other three signals except that the fluctuations occur at different times on each path. On the PR-17-to-UW signal the frequency minimum occurs near 0000 UT; on the WWV-20-to-SU signal this minimum occurs near 0004 UT; and

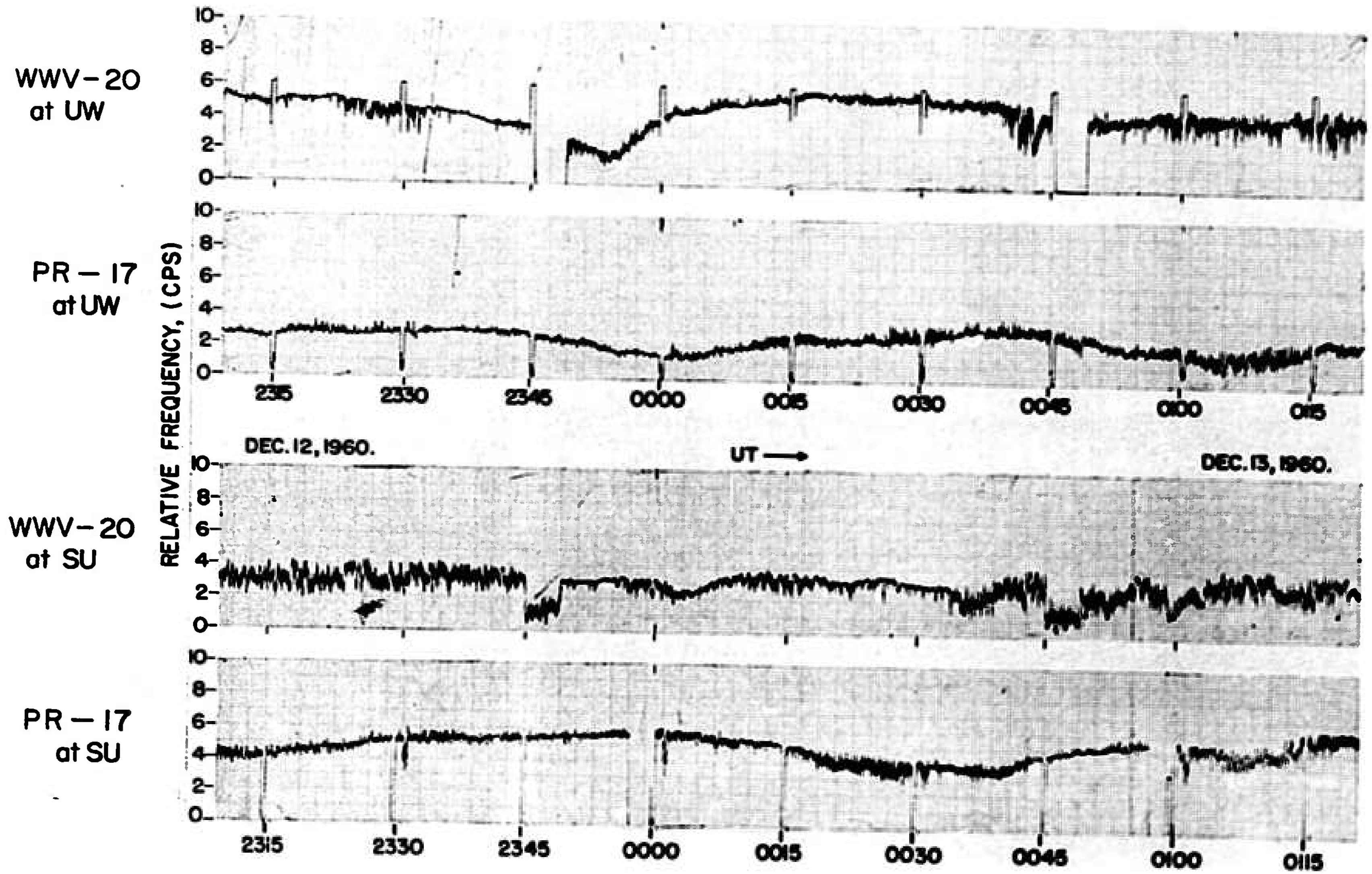


FIG. 2. FREQUENCY RECORDINGS FOR TRAVELING IONOSPHERIC DISTURBANCE OF 12 AND 13 DECEMBER 1960.

TABLE 1 TRAVELING IONOSPHERIC DISTURBANCES OBSERVED BETWEEN OCTOBER 1960 AND APRIL 1961

No.	Time (UT)	Description of Frequency Recordings	Characteristics of TID	Magnetic Field Data
1	2330 Dec 12 to 0100 Dec 13, 1960	V-shaped frequency fluctuation. Seen successively on all four paths. Reference time: WWV-20-to-UW path (2354), PR-17-to UW path (0000), WWV-20-to-SU path (0004), PR-17-to- SU path (0040). Refer to Figs. 2, 3 and Section III A	Speed $\geq$ 1600 km/hr Period $\gtrapprox$ 50 min Length $\geq$ 1300 km	K_p = 4.0 A_p = 18
2	1845 to 2045 Jan 8, 1961	Multiple modes. Frequency of one mode remains almost constant; frequency of disturbed mode varies quasi-sinusoidally. Seen successively on all four paths. Reference time: WWV-20-to-UW path (1914), PR-17-to-UW path (1921), WWV-20-to-SU path (?), PR-17-to-SU Path (1956). Simultaneous and sudden frequency increase at 1618 UT on all four paths precedes TID.	Speed $\geq$ 1700 km/hr Period $\gtrapprox$ 60 min	K_p = 4.33 A_p = 22 A sudden commencement of a geomagnetic storm occurs at 1618 UT.
3	2200 Feb 7 to 0030 Feb 8, 1961	Four consecutive quasi-sinusoidal frequency fluctuations. Seen successively on two paths only. Reference time: WWV-20-to-UW path (2332), WWV-20-to-SU path (2345).	Speed uncertain Period $\gtrapprox$ 30 min Traveling along the east coast of the United States.	K_p = 3.67 A_p = 11
4	1745 to 1930 Feb 17, 1961	Multiple modes. Frequency of one mode remains almost constant; frequency of disturbed mode varies quasi-sinusoidally. Seen successively on all four paths. Reference time: WWV-20-to-UW path (1812), PR-17-to-UW path (1831), WWV-20-to-SU path (1840), PR-17-to-SU path (1852). Simultaneous and sudden frequency fluctuations on all four paths near 1733 UT precede the TID. Refer to Fig 6.	Speed $\geq$ 1800 km/hr Period $\gtrapprox$ 45 min Length $\geq$ 1350 km	K_p = 4.33 A_p = 28 Among the five disturbed days of the month. A sudden impulse (10γ) at 1733 UT is observed on Stanford magnetogram.
5	2030 to 2215 Feb 17, 1961	Multiple modes. Frequency of one mode remains almost constant; frequency of disturbed mode varies quasi-sinusoidally. Seen successively on all four paths.	Speed $\geq$ 2400 km/hr (or $\gtrapprox$ 2750 km/hr) Period $\gtrapprox$ 45 min	K_p = 3.67 A_p = 28 Among the five disturbed days of the month.

		Reference time: WWV-20-to-UW path (2105), PR-17-to-UW path (2115), WWV-20-to-SU path (2119), PR-17-to-SU path (2135). Simultaneous and sudden frequency decrease at 2028 UT on all four paths precedes TID. Refer to Fig. 5 and Section IIIB.		A sudden commencement of a geomagnetic storm occurs at 2028 UT. (17γ drop shown on Stanford magnetogram.)
6	1600 to 1700 Mar 18, 1961	Multiple modes. Frequency of one mode remains constant; frequency of disturbed mode is higher and varies quasi-sinusoidally. Seen successively on three paths. Reference time: WWV-20-to-UW path (1628), WWV-20-to-SU path (1632), PR-17-toSU path (1650).	Speed uncertain Period ≳ 30 min	K_p = 3.67 A_p = 12
7	0000 to 0230 Mar 30, 1961	Sudden frequency decrease followed by slow frequency increase to the original value in more than ½ hr. Seen successively on three paths. Reference time: WWV-20-to-UW path (0027), PR-17-to-UW path (0117), WWV-20-to-SU path (0127).	Speed uncertain Period ≳ 45 min	K_p = 2.67 A_p = 10
8	1600 to 1830 Apr 13, 1961	Multiple modes. Frequency of one mode remains constant; frequency of disturbed mode varies quasi-sinusoidally. Seen successively on all four paths. Reference time: WWV-20-to-UW path (1645), WWV-20-to-SU path (1659), PR-17-to-UW path (1703), PR-17-to-SU path (1734). Simultaneous and sudden frequency decrease at 1452 UT on all four paths precedes TID. Refer to Fig. 7.	Speed ≥ 1450 km/hr Period ≳ 90 min Length ≥ 2200 km	K_p = 5.33 A_p = 15 A sudden commencement of a geomagnetic storm occurs at 1452 UT.
9	2200 to 2400 Apr 16, 1961	Multiple modes. Frequency of one mode remains constant; frequency of disturbed mode varies quasi-sinusoidally. Seen successively on all four paths. Reference time: WWV-20-to-UW path (2233), WWV-20-to-SU path (2247), PR-17-to-UW path (2300), PR-17-to-SU path (2318).	Speed ≥ 1600 km/hr Period ≳ 72 min Length ≥ 2000 km	K_p = 3.67 A_p = 13

Note: The K_p index is the geomagnetic planetary 3-hr range index which is the mean standardized K-index from twelve observatories between geomagnetic latitudes 47 and 63 deg. The A_p index is the daily "equivalent amplitude" of magnetic activity.

on the PR-17-to-SU signal the minimum occurs still later, at 0040 UT. This series suggests a TID moving approximately from north to south and intercepting the four paths successively.

Figure 3 shows frequency-amplitude-time displays of the same traveling disturbance for two of the four paths, i.e., PR-17 to both the UW and SU. There are no magnetic-tape recordings for the other two paths during this period. The time scale of the two frequency-spectra in Fig. 3 is displaced by about 37 min to exhibit the similarities of the V-shaped inflection caused by the TID. The details of the frequency fluctuation are not identical, because in 37 min the disturbance has traveled several hundred kilometers over which distance its shape may have changed. However, the general characteristics of this traveling disturbance can still be identified by the characteristic drop in frequency followed by a rise at a faster rate.

The time interval between the passage of the TID through the nothernmost path (WWV-20-to-UW) and through the southernmost path (PR-17-to-SU) is about 45 min. The minimum distance between these two paths is about 1200 km. Therefore, the velocity of the traveling disturbance, assuming that the velocity is constant, is equal to or greater than 1600 km/hr.

Virtual-height variations measured at Boulder, Colorado; White Sands, New Mexico; Washington, D. C.; and Puerto Rico during the period when the TID occurred are plotted in Fig. 4. The curves are obtained from the ordinary rays of the ionograms recorded at the respective stations once every 15 min. The virtual-height variations at Boulder show a distinctive ripple near 0015 UT and those at White Sands a ripple near 0045 UT. The maximum positive slope of the ripple near 0000 UT measured at Boulder (Fig. 4) correlates with the frequency minimum at 0004 UT on the WWV-20-to-SU path (Fig. 2), and the maximum positive slope of the ripple near 0040 UT at White Sands (Fig. 4) correlates with the frequency minimum at 0040 UT of PR-17-to-SU. Although the virtual-height variations are obtained from ionograms taken at 15-min intervals, and even though Boulder and White Sands are not located exactly on the transmission paths (refer to Fig. 1), time correlation between the maximum positive slopes of ripples and frequency minima is very good.

It is also noticed, in Fig. 4, that no clearly similar "ripples" are seen during the period on virtual-height-variation plots at Washington, D. C., or at Puerto Rico, suggesting that this particular TID did not affect the east coast of the United States.

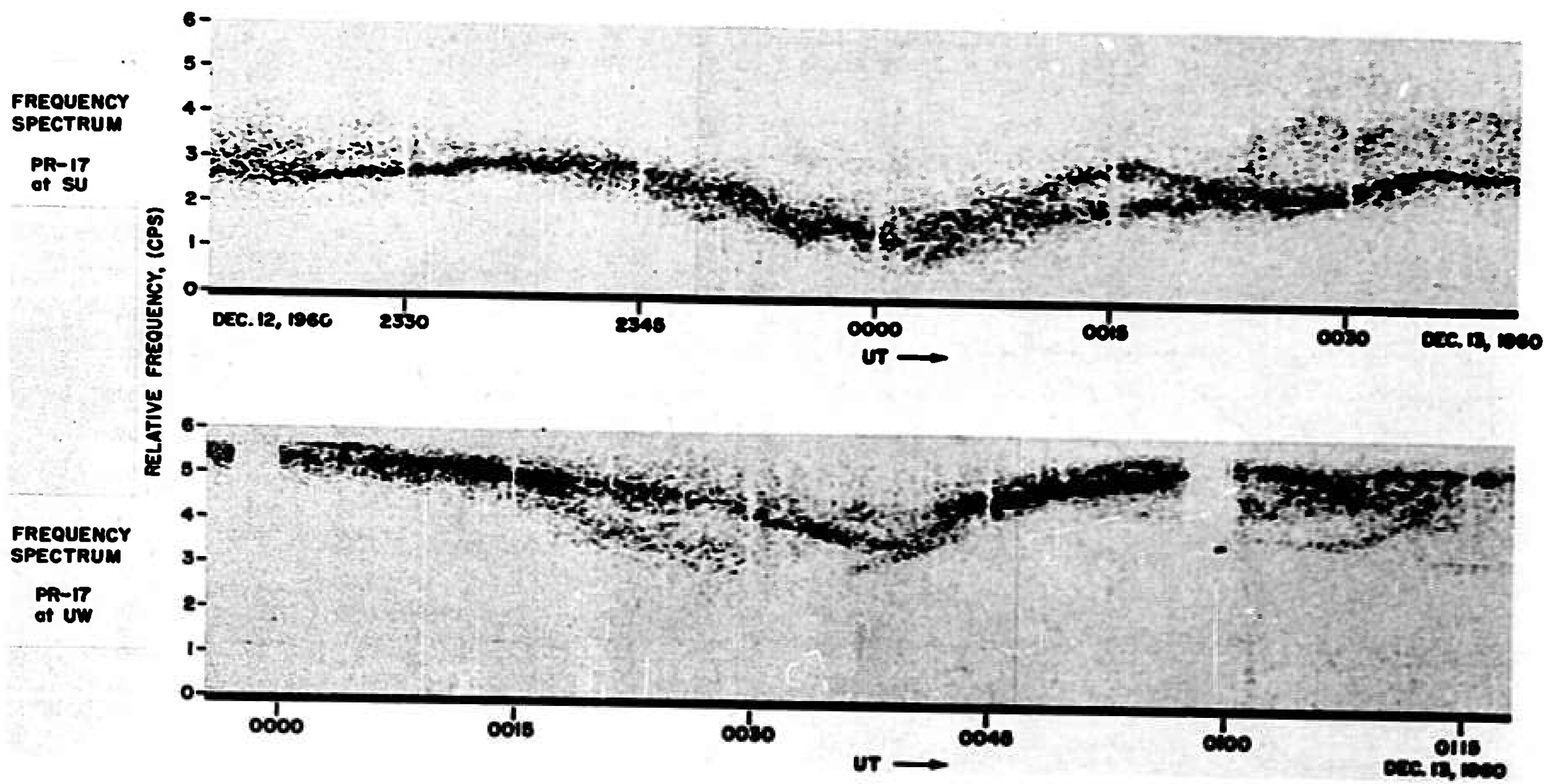
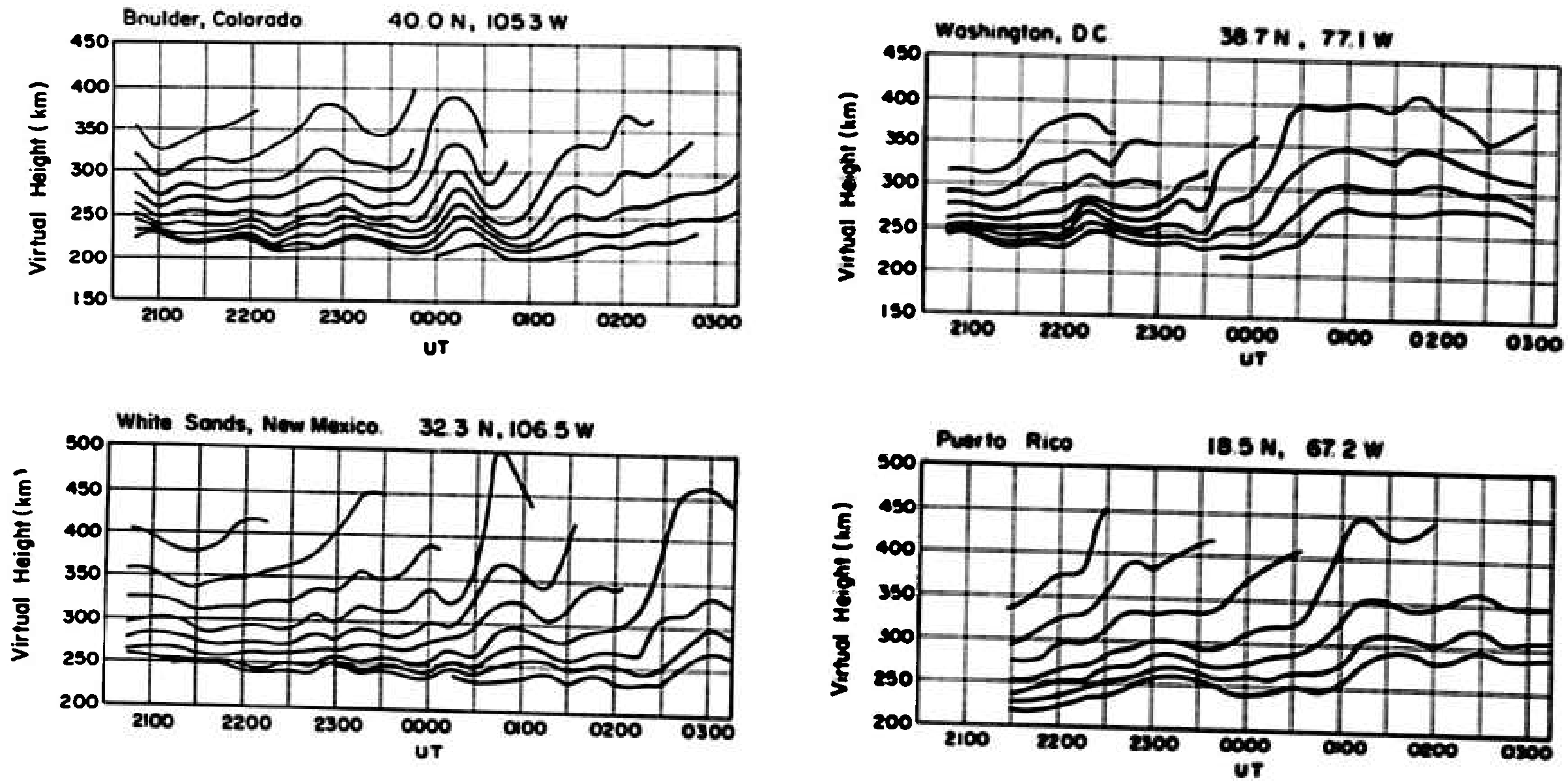


FIG. 3. FREQUENCY SPECTRUM FOR THE TRAVELING IONOSPHERIC DISTURBANCE OF 12 AND 13 DECEMBER 1960.



VIRTUAL HEIGHT VARIATIONS

(from 2100 UT Dec 12, 1960 to 0300 UT Dec 13, 1960)

FIG. 4. VIRTUAL-HEIGHT VARIATIONS AT BOULDER, COLORADO, WHITE SANDS, NEW MEXICO, WASHINGTON, D.C., AND PUERTO RICO FROM 2100 UT, 12 DECEMBER 1960 TO 0300 UT, 13 DECEMBER 1960.

Three-frequency h-f backscatter soundings at Stanford University, similar to those used by Valverde [Ref. 17], have been examined for TID's during the period from 2300 UT, 12 December, to 0100 UT, 13 December 1960. None could be discerned. However, the maximum range at which disturbances can be seen by these sounders is about 1500 km. The evidence suggests that the wavefront of this disturbance was not large enough to cover the east and west coasts of the United States. Thus, this particular disturbance must have traveled through the central part of the United States from north to south. From the Boulder and White Sands data in Fig. 4 and the frequency recording in Fig. 2, the TID appears to be a disturbance of electron density in the F-region of the ionosphere with a period of about 50 min. With its velocity determined to be greater than 1600 km/hr, the disturbance must have had a spatial length greater than 1300 km.

B. TRAVELING IONOSPHERIC DISTURBANCE OF 17 FEBRUARY 1961

Two TID's were detected on 17 February 1961. One is shown in Fig. 5. Frequency fluctuations on the four paths are displayed in the same order as those in Fig. 2.

The received frequencies increase suddenly and simultaneously on all four paths at 2028 UT. This increase is not caused by a TID, since the paths are separated by several hundred kilometers. Sudden frequency changes of this sort have been correlated with the occurrence of solar flares or sudden changes of the earth's magnetic field [Ref. 21]. This frequency increase at 2028 UT correlates with the sudden commencement of a magnetic storm. A small (17-gamma) but sudden decrease of the earth's magnetic field was recorded at that time at Stanford University.

Since the counter-type recording system responds only to the strongest mode of propagation at any given time, when several modes of approximately equal strength are propagating at the same time, the recorded frequency will be that of whichever mode happens to be strongest. Thus, the frequency may jump at random from one value to another, depending on the relative strengths of the modes. On the WWV-20-to-SU path in Fig. 5, two modes of approximately equal strength, and with frequencies differing by about 1/2 cps, have been propagating prior to 2045 UT. However, after 2049 UT, an ionospheric disturbance caused the frequency of one mode to vary quasi-sinusoidally with a minimum near 2100 UT and a maximum near 2110 UT, while the frequency of the other mode remained almost unaffected throughout the period. The frequencies of the two modes coincided at 2105 UT.

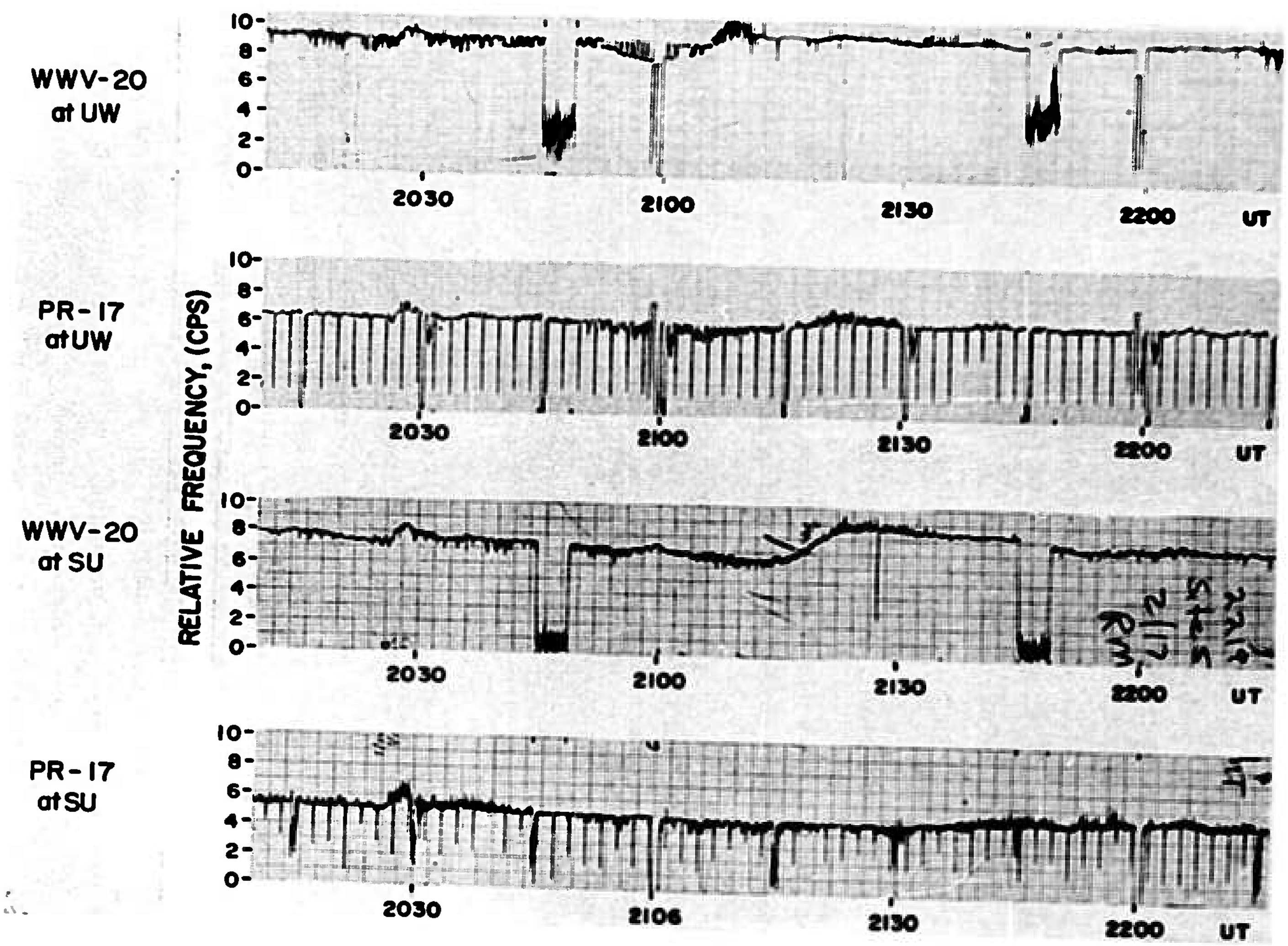


FIG. 5. FREQUENCY RECORDINGS FOR THE SECOND TRAVELING IONOSPHERIC DISTURBANCE OF 17 FEBRUARY 1961.

Similar, though less distinctive, features are also noticed on the frequency recordings of the other three paths. On the frequency recordings of PR-17 at UW, the frequency of one mode is almost constant, while the frequency of the disturbed mode is lower than that of the undisturbed mode before 2115 UT and higher afterward. The frequencies of the two modes coincide at 2115 UT. On the WWV-20-to-SU path, the sinusoidal frequency variation from 2100 to 2145 UT indicates the presence of the disturbed mode. As contrasted to the other three paths, the frequency recordings of WWV-20 at SU appear to lack a mode of propagation whose frequency is constant throughout that period. This absence of multiple modes can be interpreted as meaning that only one mode, the undisturbed one, is propagating during that period, or, if more than one mode is propagating, that the disturbed mode is much stronger than any undisturbed component. On the PR-17-to-SU path, the frequency of the disturbed mode is lower than that of the undisturbed mode before 2135 UT and higher afterwards. The frequencies of the two modes coincide at 2135 UT.

Using the time when the frequencies of the different modes coincide as a reference, the ionospheric disturbance intercepts the WWV-20-to-SU path at 2105 UT, the PR-17-to-UW path at 2115 UT, the WWV-20-to-SU path around 2119 UT, and the PR-17-to-SU path at 2135 UT. This sequence shows that an ionospheric disturbance is traveling in the central part of the United States generally from north to south. It covers in 30 min a distance greater than 1200 km, and its period of disturbance is about 45 min on any path. Therefore, the TID has a speed greater than 2400 km/hr and a spatial length over 1800 km.

C. DISCUSSION OF TRAVELING IONOSPHERIC DISTURBANCES

Traveling ionospheric disturbance No. 1 (Figs. 2 and 3), described previously, caused a V-shaped inflection to appear on frequency recordings. Disturbance No. 7, which was detected by the sudden frequency decrease followed by a slow frequency increase, also appears to have caused a V-shaped fluctuation or unequal slopes on the frequency recordings. The time when the frequency is minimum is used as the reference time for the TID to cross a stable-frequency transmission path. All other TID's--i.e., Nos. 2, 3, 4, 5, 6, 8, and 9--produced quasi-sinusoidal frequency variations. Multiple modes appear in Nos. 2, 4, 5, 6, 8, and 9, with the frequency of one mode remaining almost constant throughout the period under study, while the frequency of the disturbed mode varies quasi-sinusoidally. The time when the frequencies of the disturbed and the undisturbed modes coincide is used as the reference time for the TID to cross a transmission path.

Sudden frequency changes that occurred simultaneously on all four paths preceding traveling ionospheric disturbances are found in four cases, (Nos. 2, 4, 5, and 8). In three cases, (Nos. 2, 5, and 8), the sudden frequency changes corresponded to sudden commencements of geomagnetic storms, and in the other case (No. 4) the frequency change corresponded to sudden impulses found in Stanford magnetograms. Disturbance No. 5 is illustrated in Fig. 5 and has been described in Section III B. The frequency recording of TID's Nos. 4 and 8 are shown in Figs. 6 and 7 respectively. Note the simultaneous frequency fluctuations at 1733 UT 17 February (Fig. 4) and at 1452 UT 13 April (Fig. 8), which preceded the TID's. The TID's have the usual characteristic that the frequency of the disturbed mode varies quasi-sinusoidally. The reference time and other details of the disturbances are described in Table I.

The speed at which a disturbance travels is calculated from the time lapse between the crossing of the northernmost path (i.e., WWV-20-to-UW) and that of the southernmost path (i.e., PR-17-to-SU). From this it can be assumed that the disturbance must travel a minimum distance of about 1200 km between these two paths. The period of a disturbance is taken to be an average of the duration of the disturbances observed on the frequency recordings corresponding to the different transmission paths. The spatial length of the disturbance is then taken to be the product of the estimated speed and average period of the TID.

The layout of the four transmission paths is such that ionospheric disturbances traveling in the central part of the United States are most easily detected, as substantiated by the experimental results. Six TID's (Nos. 1, 2, 4, 5, 8, and 9) affect the four paths successively and two (Nos. 6 and 7) cause disturbances on only three paths. During TID No. 2, only two paths (WWV-20-to-SU and WWV-20-to-UW) are disturbed, suggesting that No. 2 might have traveled from north to south along the east coast of the United States, and that the disturbance was damped before it reached the two transmission paths from Puerto Rico.

Figure 8 is a gnomonic projection of the United States on which the great-circle path between any two points is represented by a straight line joining the two points. If the ionospheric distance is assumed to travel with constant speed along a great-circle path, then the path of the disturbance can be determined uniquely by knowing the exact time

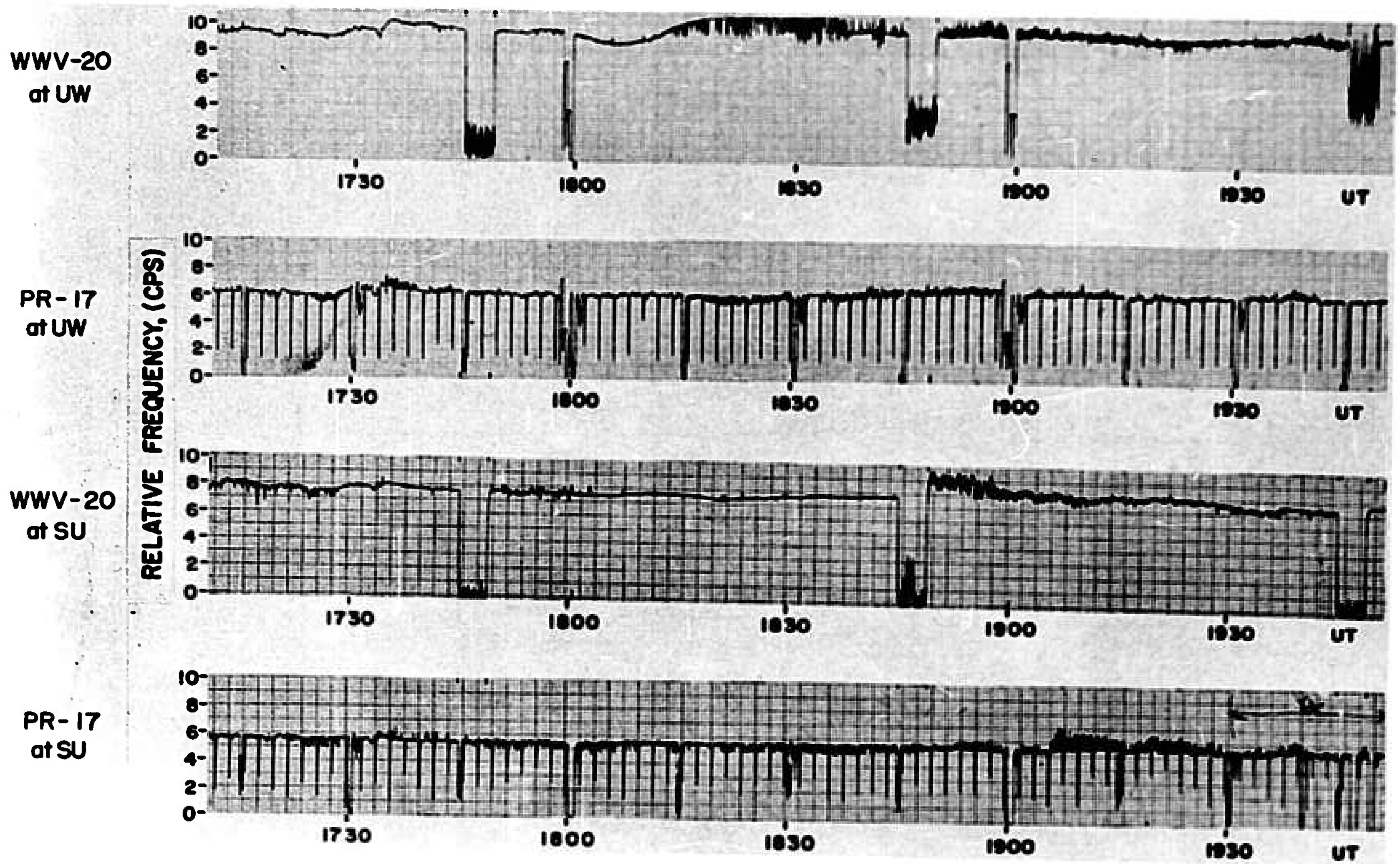


FIG. 6. FREQUENCY RECORDINGS FOR THE FIRST TRAVELING IONOSPHERIC DISTURBANCE OF 17 FEBRUARY 1961.

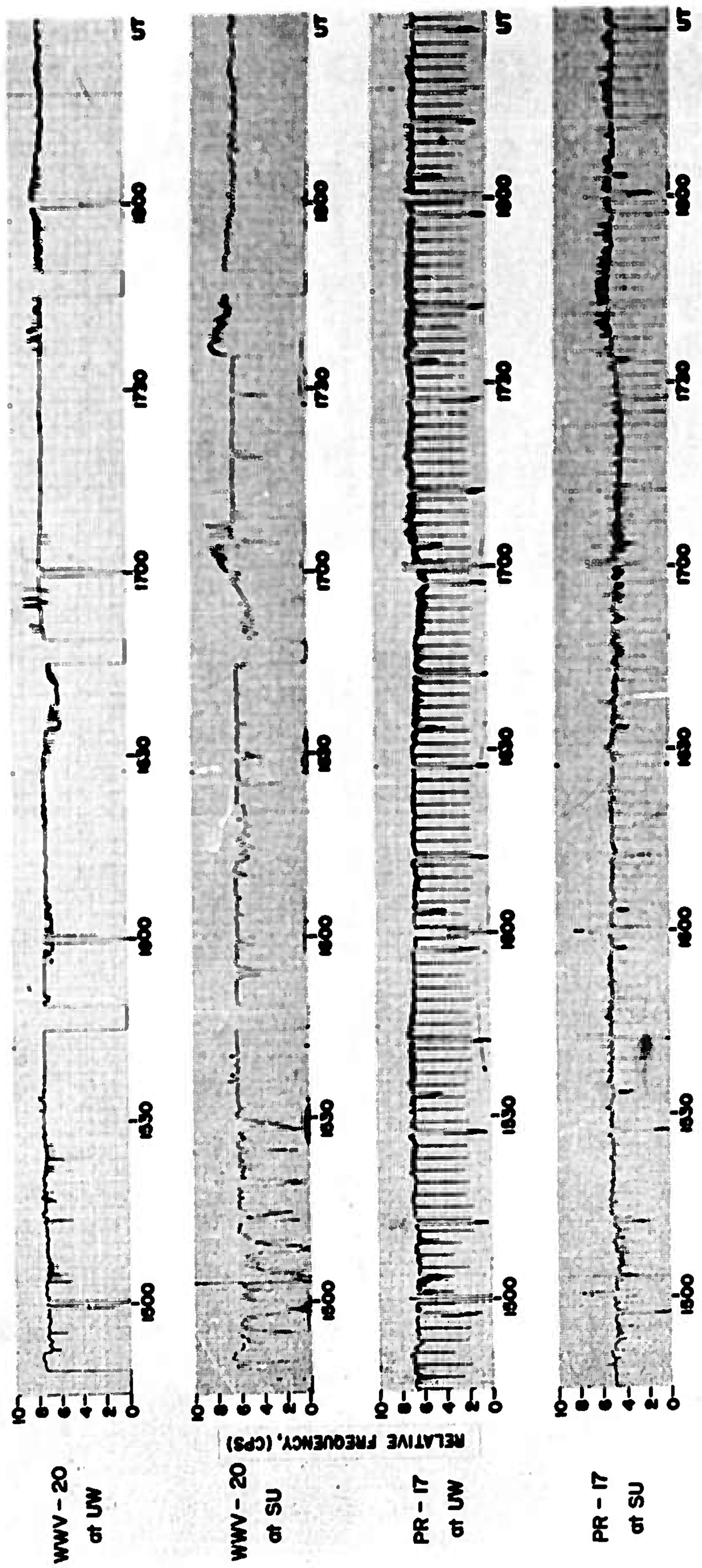


FIG. 7. FREQUENCY RECORDINGS FOR THE TRAVELING IONOSPHERIC DISTURBANCE OF 13 APRIL 1961.

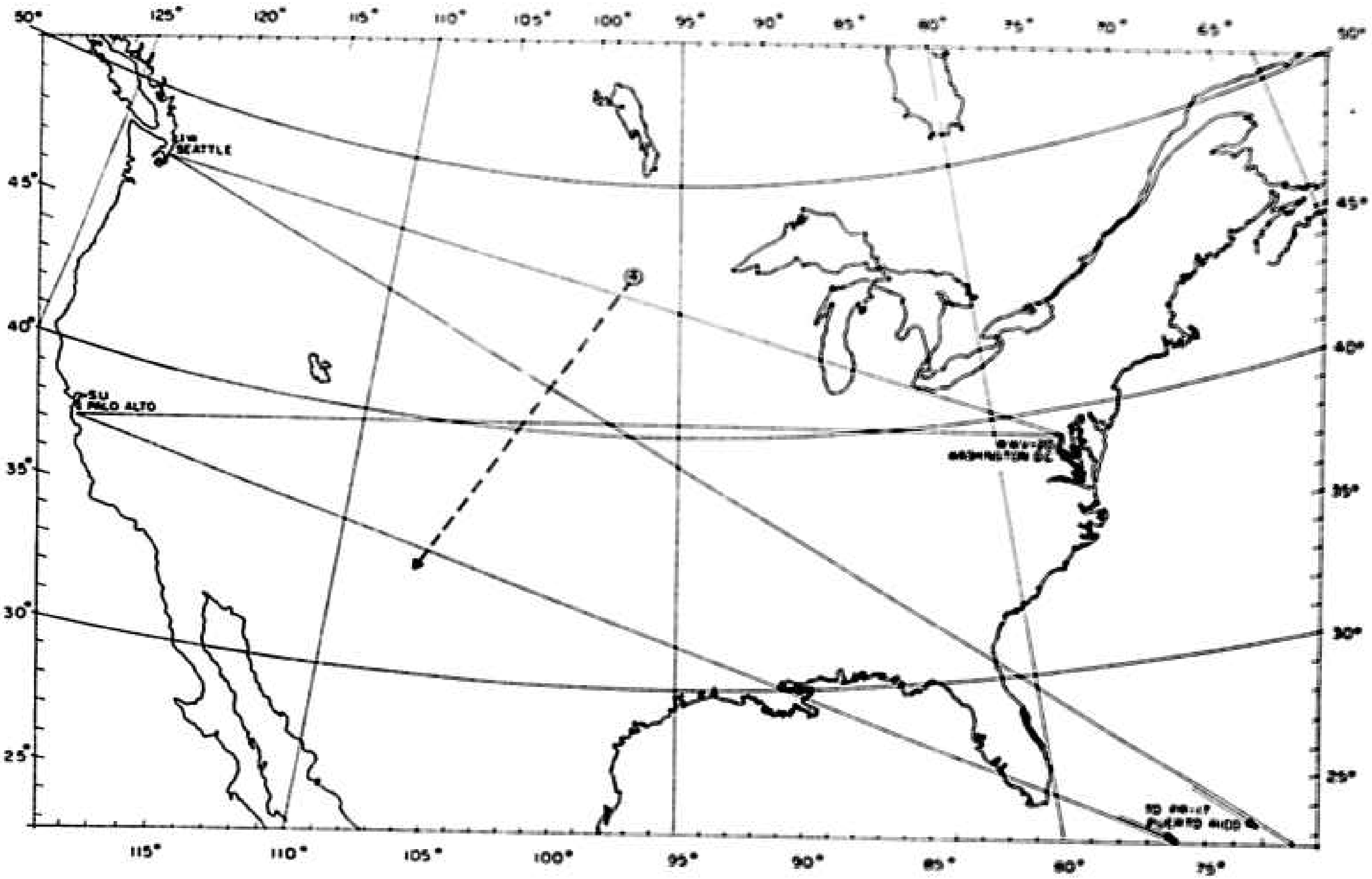


FIG. 8. GREAT-CIRCLE PATHS OF WWV-20 AND PR-17 TO SU AND UW ON GNOMONIC PROJECTION.

that the TID intercepts each of the four different paths. By employing a map such as shown in Fig. 8, the problem of spherical geometry is simplified into a problem of plane geometry. Of the nine detectable traveling ionospheric disturbances, five (Nos. 1, 4, 5, 8, and 9) are observed to intercept all four paths. The refe- ..e time on each path is measured to the nearest minute, and the respective paths of travel can be investigated. However, only one (No. 4) of the five disturbances produced a consistent result. Other disturbances either described a path of travel not intercepting all the transmission paths or required a speed much greater than the speed of sound in the F_2 layer. The path for TID No. 5 is shown in Fig. 8, and the direction is 208 °E of N. According to this path, the speed of the ionospheric disturbance, covering 1375 km is about 30 min, is approximately 2750 km/hr (compared with the speed of 2400 km/hr previously estimated in Section III B).

D. COMMENTS ON THE DIRECTION OF TRAVEL AND CONSTANCY OF SPEED

Valverde [Ref. 17] observed that the speed of large-scale TID's was constant, but that the direction of travel usually varied (on the order of 10 deg) during the interval of about 1/2 hr. Thomas [Ref. 12] suggested that disturbances at latitudes near the zone of maximum auroral and magnetic activity might have a higher velocity than those at lower latitudes. Our results appear to support the belief that large-scale TID's do change both speed and direction during the course of travel, because:

1. we cannot locate physically possible routes for the disturbances by assuming a constant speed and a constant direction, and
2. most disturbances require much more time to travel between the two southern paths than between the two northern paths.

It should be noted also that the accuracy of the time-of-crossing measurement does not allow direction of travel to be determined within an accuracy of 10 deg, even when the disturbances do travel with a constant speed and a constant direction. However, it is certainly possible to know that the general direction of travel is from north to south, and that changes in velocity and/or direction do occur.

E. RELATIONSHIP BETWEEN LARGE-SCALE TID's AND SUDDEN COMMENCEMENTS OF GEOMAGNETIC STORMS

Because out of nine traveling ionospheric disturbances detected by this technique, three (Nos. 2, 4, and 8) were preceded by sudden commencements of magnetic storms and one (No. 3) was preceded by a sudden impulse found in the Stanford magnetogram, an investigation was made to see if TID's generally follow sudden commencements of magnetic storms. During the period from October 1950 to April 1961, 22 sudden commencements were reported [Ref. 22] by magnetic observatories in northern America. The frequency recordings of the four stable-frequency transmission paths were carefully re-examined for a period of about 6 hr after these sudden commencements. At the time of onset of each sudden commencement, simultaneous, abrupt fluctuations are always observed on the frequency recordings of all available paths. During the relatively calm period after the sudden commencements, and before the onset of the comparatively strong geomagnetic activity that usually appears several hours after the sudden commencements, the frequency fluctuations of all available paths are usually well correlated for a period of time varying between 1/2 to 3 or 4 hr Then, on many occasions, the frequency fluctuations on all available paths began to differ in a way that suggests the presence of TID's. In many instances, specific disturbances can be picked out The results are tabulated in Table 2, which can be summarized as follows:

1. Twenty-two sudden commencements (a to u) were reported during the period from October 1960 to April 1961
2. The frequency recordings on 11 cases (d, f, g, l, m, n, o, q, r, s, and u) provide no information, because either the equipment was not functioning properly, or, for a large number of cases, the propagation conditions were poor as a result of low MUF or already strong geomagnetic disturbance.
3. No TID is observed after three sudden commencements (c, f, and k). For c and f, severe geomagnetic disturbances set in about 4 hr after the sudden commencements and no TID is observed during the 4-hr period. For k, a TID is not observed for about 6 hr after the sudden commencement on two available paths only; the other two paths were not operating.
4. TID's are strongly suggested on frequency recordings after four sudden commencements (a, b, h, and t). Multiple modes with the frequency of the disturbed mode varying quasi-sinusoidally are found on the frequency recordings on more than one of the available paths.
5. TID's are positively recognized after four sudden commencements (e, i, p, and r). TID's in i, p, and r, of Table 2 are the same as TID Nos. 2, 5, and 8 respectively reported in Table 1. The TID observed in e of Table 2 is not included in Table 1 because only two paths were functioning properly at that time.

In short, of the 11 sudden commencements having useful frequency recordings, TID's are not found after three sudden commencements, are highly possible after four sudden commencements, and are definitely present after the other four sudden commencements.

TABLE 2 RELATIONSHIP BETWEEN LARGE-SCALE TID'S WITH SUDDEN COMMENCEMENTS (SC'S) OF GEOMAGNETIC STORMS

Sudden Commencement		Description of Frequency Recordings of 6-hr Period after SC	Remarks
No.	Date and Time (UT)		
a	Oct 24, 1960 1452	Sudden frequency fluctuation at 1452 on all four paths. WWV-20-to-UW paths out of order after 1515. From 1500 to 1630, frequency fluctuations on three paths well correlated and relatively calm. From 1630 to 2100, multiple modes with TID characteristics seen on three paths.	Two successive TID's suggested by frequency recordings; neither can be positively recognized.
b	Nov 3, 1960 2227	Sudden frequency fluctuation at 2227 on all four paths. From 2230 to 0230, frequency fluctuations not correlated among four paths. All paths were disturbed, not to the same degree, but in the following order: WWV-20-to-UW, WWV-20-to-SU, PR-17-to-UW, PR-17-to-SU.	One TID suggested by UW recordings alone; another TID suggested by SU recordings alone. No TID clearly seen in all four frequency recordings.
c	Nov 12, 1960 1349	Class 3^{+} solar flare at 1326 caused radio fadeout on all four paths; only WWV-20-to-UW path recovered in time to catch SC at 1349. All paths recovered from fadeout after 1530. From 1530 to 1800, frequency fluctuations relatively calm and reasonably correlated among all paths. Violent frequency fluctuations on all paths after 1800.	No TID observed for about 4 hr after the SC (1400 to 1800). Strong geomagnetic activities set in after 1800.
d	Nov 15, 1960 1304	No information because all paths disturbed by severe geomagnetic storms.	No information
e	Nov 24, 1960 2053	Sudden frequency drop at 2053 on all four paths. Frequency fluctuations well correlated among all paths from 2100 to 2245. TID observed from 2240 to 2400 on two paths. PR signal not transmitting during that period.	TID observed; not included in Table 1, because only two paths functioning properly.
f	Nov 30, 1960 1909	Sudden frequency jump at 1909 on two paths (only 2 paths functioning). Frequency fluctuations well correlated on all available paths from 1909 to 2300. Violent frequency fluctuations after 2300.	No TID observed for 4-hr after the SC (1900-2300).
g	Nov 30, 1960 2358	Sudden frequency jump at 2358 on all available paths. Frequency fluctuations violent after 2358 because of strong magnetic activity.	No information for TID because of strong magnetic activity.
h	Dec 7, 1960 1804	Sudden frequency fluctuation at 1804 on all four paths. TID suggested on UW recordings during 2030 to 2200, and during 0000 to 0100, Dec 8, 1960.	Two TID's suggested on UW frequency recordings, but SU recordings not properly operated to confirm observation.

i	Jan 8, 1961 1618	Sudden frequency jump at 1618 on all four paths. Frequency fluctuations well correlated among four paths from 1618 to 1845. TID observed from 1845 to 2045.	TID (No. 2 in Table 1) observed about 3 hr after SC.
j	Feb 3, 1961 0908	No signals received because of low MUF	No information.
k	Feb 4, 1961 1331	No UW frequency recordings. SU frequency recordings very disturbed	No TID observed on the two available paths.
l	Feb 4, 1961 1829	No data available; transmission paths very disturbed.	No information.
m	Feb 6, 1961 0106	No signal received because of low MUF.	No information.
n	Feb 13, 1961 0253	No signal received because of low MUF.	No information.
o	Feb 16, 1961 0044	No signal received because of low MUF.	No information.
p	Feb 17, 1961 2028	Sudden frequency decrease at 2028 on all four paths. TID observed from 2045 to 2200.	TID (No. 5 in Table 1) observed about 40 min after SC.
q	Mar 5, 1961 0933	No signals received because of low MUF.	No information.
r	Mar 9, 1961 1327	No useful data available because of low MUF as well as disturbed condition.	No information.
s	Mar 13, 1961 2316	No useful data because of low MUF after 0030, Mar. 14, 1961.	No information.
t	Mar 27, 1961 1503	Sudden frequency jump at 1503 on all four paths. Frequency fluctuations well correlated among four paths from 1500 to 1630. TID's suggested from 1630 to 1930.	TID's suggested on three of the four frequency recordings; however, none positively confirmed.
u	Mar 31, 1961 1511	No useful data available because of equipment failure.	No information.
v	Apr 13, 1961 1452	Sudden frequency jump at 1452 on all four paths. TID observed from 1630 to 1800.	TID (No. 8 in Table 1) observed about 2 hr after the SC.

IV. DISCUSSION

Munro [Refs. 2, 3] considered that traveling disturbances in the ionosphere are associated with disturbances in the atmosphere in the form of traveling pressure waves that cause a redistribution of ionization. Martyn [Ref. 23] developed a theory of horizontally traveling cellular atmospheric waves and later [Ref. 24] suggested that perturbation of F-region ionization might be the result of turbulence in lower regions. Regardless of how a TID originates, we may assume that such a disturbance is a traveling atmospheric wave of ellipsoidal shape in the F-region which causes a redistribution of ionization as it travels along.

Figure 9(a) is a representation of a typical ionospheric disturbance traveling from north to south and affecting the one-hop mode of a signal traversing the WWV-20-to-SU path. Contours showing the heights of assumed concentric elliptical troughs of a constant electron density which reflect the signal of interest are shown in Fig. 9(b). As the disturbed region travels with velocity v, the signal is reflected along AA'. The profile of AA' is plotted in Fig. 9(c). If, for simplicity, only the geometrical raypath is investigated, the doppler shifts as the signal is reflected along AA' are

$$\Delta f/f = (2\mu/c) \cos \theta,$$

where θ = angle of incidence in deg,

f = transmitted frequency in cps,

Δf = doppler shift in cps,

c = velocity of transmission in m/sec, and

μ = downward vertical velocity in m/sec = $-dh/dt$.

Since $dx = v\ dt$,

$$\Delta f/f = (2v/c) \cos \theta\ (-dh/dx).$$

If v is assumed constant and θ varies only slightly during the period of interest, then Δf varies as $(-dh/dx)$, a quasi-sinusoidal curve as shown in Fig. 9(d), depending on the slope of the constant ion density of the disturbance. If the TID intercepts a transmission path differently, so that the signal is reflected along BB' or CC' instead of along AA', then the amplitude and period of frequency fluctuations will be varied, but the general quasi-sinusoidal form of the frequency fluctuations will remain unchanged. If the one-hop and two-hop modes propagate at the same time with approximately equal strength, and if the wavefrontof the TID

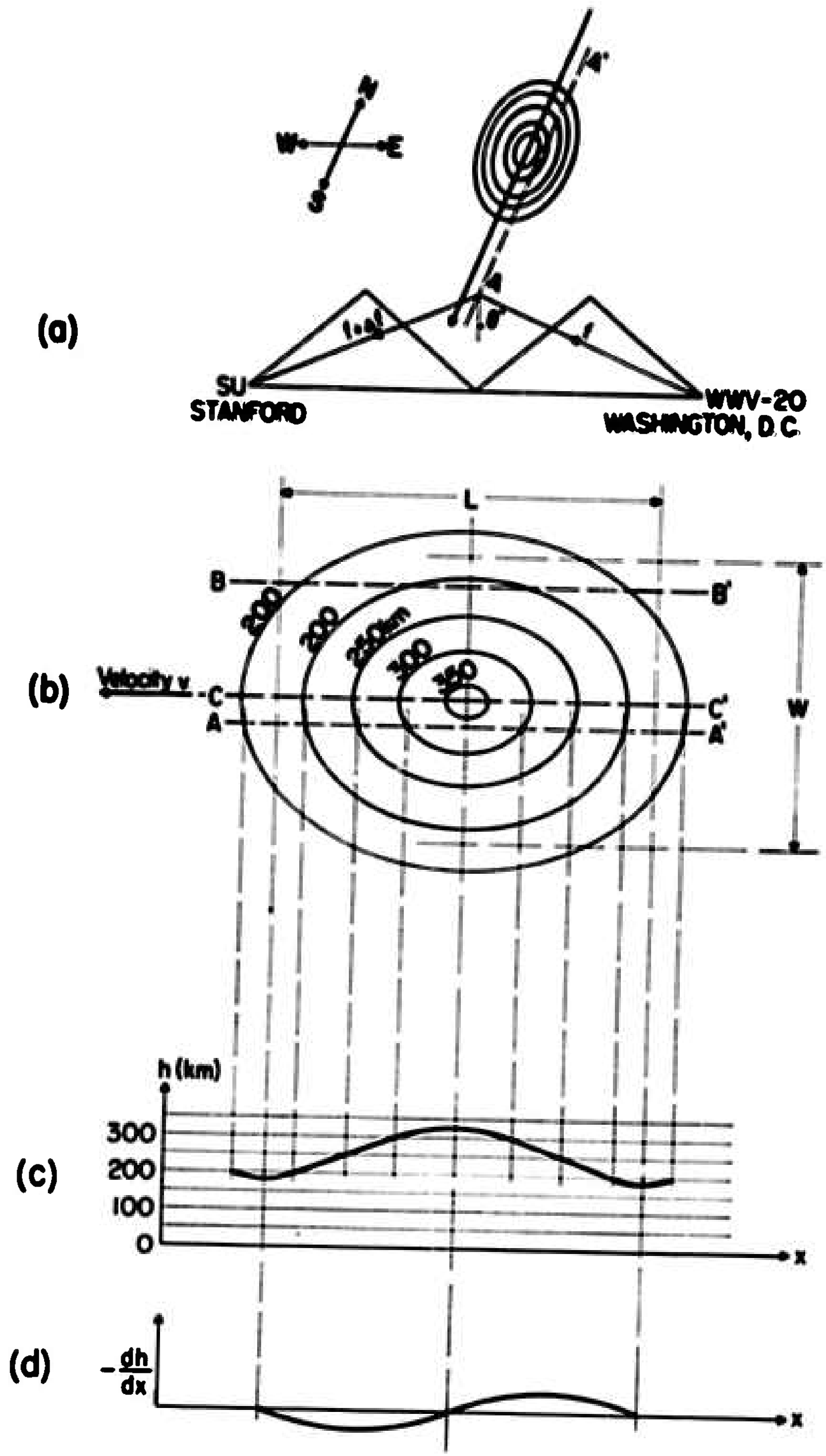


FIG. 9. POINT-REFLECTOR MODEL OF A TRAVELING IONOSPHERIC DISTURBANCE.

is not wide enough to affect the two-hop mode as illustrated in Fig. 9(a), then the frequency recordings will show multiple modes with the frequency of one mode being constant and that of the other being quasi-sinusoidally disturbed. If either the two-hop mode is much weaker than the one-hop mode, or the wavefront of the traveling ionospheric disturbance is wide enough to affect all the modes simultaneously, then the recordings will show predominantly a single frequency that is quasi-sinusoidally disturbed.

Traveling ionospheric disturbances Nos. 2, 3, 4, 5, 6, 8, and 9 in Table I do exhibit the features described above, which are based on the assumption of a traveling ellipsoidal trough of electron density. This fact suggests that most of the TID's detectable by this technique are in fact of the type shown in Fig. 9. If the TID is in the form of a tilted step of constant electron-density [Ref. 25] (i.e., the height of the reflection point increases monotonically during the period of disturbance), then V-shaped frequency fluctuations will be resulted, as noticed in disturbances Nos. 1 and 7.

In the southern hemisphere during winter months, the direction of travel is reported to be 30° E of N by Munro [Ref. 4], from south to north by Heisler [Ref. 8], and from 300° to 90° E of N by Price [Ref. 5]. In the northern hemisphere during winter months the direction of travel is reported to be within ±25° from geomagnetic north to south by Valverde [Ref. 13], from north to south by Heisler [Ref. 8], from east to west by Beynon [Ref. 7], toward the southeast by Toman [Ref. 6], and from 150° to 180° E of N by Thomas [Ref. 9]. It should be noticed, however, that Beynon's results were based on only two points situated in the east-west direction, and the TID observed by Toman could be due to irregularities in the E-region. Therefore, most authors are in general agreement regarding the direction of travel for ionospheric disturbances in the F_2 region during winter months. This direction is generally from geomagnetic north to south in the northern hemisphere, and from geomagnetic south to north in the southern hemisphere.

Of the nine traveling ionospheric disturbances reported here and found by means of multiple-station stable-frequency transmissions, the periods are from 30 to 90 min, the velocities are from 1450 to greater than 2400 km/hr, and the spatial lengths are from 1300 km to greater than 2400 km. The wavefronts of disturbances cannot be determined accurately, but some of them can be estimated to be greater than 2000 km in width.

Except for Valverde [Ref. 17], all prefious researchers on this subject observed TID's in the F region comparatively frequently. The average velocities of the disturbances ranged from 350 to 600 km/hr, and the spatial lengths were not greater than a few hundred km. The difference in observed velocities may be due to the smaller size of these disturbances, and to the fact that these results refer to measurements at different times of the day or seasons of the year, at different geographical locations, or at different heights in the F layer, since different frequencies have been used. Thomas [Ref. 9] pointed out that the difference in height was probably the most significant factor in the discrepancy of velocities, since he observed a height gradient of velocity (average about 3.6 km/hr per km increasing with height) in the F region. However, the average velocity referred to at the foF2 level (as observed by Thomas) was about 650 km/hr, much smaller than the average velocity of the disturbances reported here.

Probably the reason that traveling ionospheric disturbances of speeds greater than 1200 km/hr in the F2 layer in non-auroral regions were not observed by all previous workers except Valverde and Tveten is because of the time resolution in records obtained from closely spaced networks. On the other hand, TID's of low speed are not observed in our experiment because of wide separations of the transmission paths. A TID with a speed of less than 1200 km/hr will take more than 1 hr to travel from the northernmost to the southernmost path. It probably will lose most of the recognizable characteristics on frequency recordings during the time interval required for the passage.

Large-scale traveling disturbances of high speed appear to be much rarer phenomena than those of smaller size and lower speed. Only nine are positively recognized here in a period of seven months, 15 (with speeds of $\geq$ 1200 km/hr) by Valverde [Ref. 17] in a period of three months and eight by Tveten [Ref. 18] in a period of one month. Valverde also reported that on several occasions, when large-scale TID's were observed on backscatter records at 17.3 Mc, the transmissions of WWV 15 and 20 Mc from Washington, D. C. to Stanford University were disrupted for periods of the order of 15 min to several hours. Such signal failure would prevent data from being taken by the technique of this report.

Beynon [Ref. 26], and Thomas [Ref. 9] found that the velocity of disturbances is independent of the K index for $K < 2.5$, but increases with the increase of magnetic activity for $K > 2.5$. Of the nine large-scale disturbances reported here, the planetary K_p index ranges from 2.67 to

5.33, with maximum occurrence at $K_p \gtrsim 4$. The limited number of detectable large-scale TID's does not provide enough information to confirm or contradict the correlation between the velocity and the magnetic activity. If the velocity of large-scale traveling disturbances does correlate with magnetic K_p index, then $K_p \gtrsim 4$ can be interpreted as the optimum condition for detection of large-scale traveling disturbances by means of simultaneous frequency recordings on geographically separated multiple paths. This condition occurs because this experimental setup is insensitive to low-speed disturbances, correlated with lower K_p index, while the rapid frequency fluctuations due to high magnetic activity, correlated with high K_p index, may be so intense and confusing that the effect of individual traveling disturbances on the frequency recordings cannot be recognized. The sudden changes of the earth's magnetic field that preceded TID's Nos 2, 4, 5, and 8 are very interesting. Although the study summarized in Table 2 cannot provide conclusive confirmation, the results seem to suggest strongly that sudden commencements of geomagnetic storms and large-scale TID's are related. If they are truly related, the obvious questions are how they are related and why some of the TID's reported in Table 1 are not preceded by sudden commencements of geomagnetic storms. It is also interesting to note that Thomas [Ref. 12] reported that in some cases quite small perturbations in the magnetogram traces coincided with enhanced velocities of traveling disturbances.

Future research on this subject should be conducted with the aid of one or more magnetometers sensitive to small and sudden changes of the earth's magnetic field. Various characteristics of TID's should be compared not only to how much the earth's magnetic field has changed but, probably more important, to how rapidly the earth's magnetic field has changed. The fact that sudden commencements of geomagnetic storms precede some TID's suggests that, if they are truly correlated, the traveling ionospheric disturbances may be caused by the same mechanism that causes the magnetic variations. A detailed study along this line will probably lead to the understanding of energy sources of traveling ionospheric waves

V. CONCLUSIONS

Traveling ionospheric disturbances have been detected by means of their effect on the simultaneous frequency recordings of four stable-frequency transmissions. Because of the wide separation of the long-distance transmission paths, the experiment is sensitive only to large-scale, high-speed TID's. These disturbances would probably not be detected on recordings made with the comparatively close-spaced networks used by many researchers in the past. From 1600 hours of data (usually from 1600 to 0200 UT) between October 1960 and April 1961, nine TID's have been positively recognized. With the assumption that ionospheric disturbances travel with constant speed in a great-circle path, it is possible to estimate speeds and spatial lengths in six instances. Velocities range from 1450 to approximately 2700 km/hr, and spatial lengths from 1300 to greater than 2000 km. The direction of travel cannot be determined accurately, but, in each case, the general direction is from north to south. The results also suggest that some of the TID's change their velocity and/or direction of travel during the passage through the four stable-frequency paths. In four cases, sudden frequency changes--three correlated with sudden commencements of geomagnetic storms and one correlated with a sudden impulse found in a magnetogram taken at Stanford--preceded the occurrence of large-scale TID's. During the same period from October 1960 to April 1961, of the 11 sudden commencements when the frequency recordings are useful for investigation, traveling ionospheric disturbances are found to be absent after three sudden commencements, highly possible after four sudden commencements, and definitely present after four sudden commencements. Although the information so far obtained is inconclusive, it is suggested that these large-scale TID's might have been launched by the same event giving rise to the sudden change of earth's magnetic field.

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